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Loading and Capacity Effects on Platform Performance in Extreme Storm Waves and Earthquakes

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ABSTRACT

Dynamic - transient loading effects from extreme storm waves and earthquakes can have important influences on the nonlinear ultimate limit state performance of fixed offshore platforms. Recorded and synthetic storm wave and earthquake time histories have been used to develop loading time histories acting on template-type platforms having natural periods in the range of 1 to 5 sec. The interactions of these loading histories with the dynamic, nonlinear, hysteretic performance characteristics of idealized systems have been analyzed. A static push-over capacity modification factor has been developed to recognize transient loading - structure performance characteristics. The results from the idealized systems have been correlated with results from time domain nonlinear analyses of platform structure systems subjected to intense wave and earthquake loadings. For the global behavior of the platforms studied, the results based on the simplified systems are in good agreement with those from the complex analyses.

INTRODUCTION

Due to the transient and dynamic aspects of most environmental loadings imposed on and induced in offshore platforms, it can be important to recognize the differences between loadings and loading effects.[1,2,3] The term "loadings" is taken to represent the forces that are imposed on an offshore structure that are fundamentally independent of how the structure responds to the imposed forces. Such forces frequently are referred to as being static even though they vary with time.

The term "loading effects" is taken to represent the internal forces that are generated within an offshore structure that are dependent on how the structure responds to the imposed forces.

Loading effects induced in an offshore structure are determined by: (a) the characteristics of the loadings, and (b) the performance characteristics of the structure, Table 1 summarizes the primary loading and structure performance characteristics (Fig. 1).

This paper addresses Fv for extreme condition wave and earthquake lateral forces developed on conventional steel, template-type platforms having natural periods (Tn) in the range of Tn = 1 to 5 sec.

Ductility (μ) is used as a primary reflector of the damage producing potential of the transient loadings. The ductility capacity of a platform (Fig. 1) is determined by the lateral displacement at which the structure can no longer support its gravity loadings (Δp) divided by the lateral displacement at which the overall system demonstrates its first significant nonlinear behavior (Δe):

$$\mu = \frac{\Delta p}{\Delta e} \quad \text{... (3)}$$

The study summarized in this paper has been focused on the performance characteristics of elastic and nonlinear, hysteretic, single-degree-of-freedom (SDOF) systems. This has been done for three reasons. The first is for simplicity in analysis and interpretation. The analyses of SDOF systems are relatively easy to perform and understand. A large number of different parameters and characteristics can be studied efficiently.

The second reason is related to the performance characteristics of the type of platforms that were of concern in this study. Generally the first two lateral orthogonal modes control the primary response characteristics of the platforms. Nonlinear behavior is often concentrated in one of the three major components that comprise the platform: the deck supporting system, the jacket, and the pile foundation. The nonlinear performance characteristics of each of these components can be different and SDOF systems can be utilized to study the importance of these differences to the loading effects induced in the platform system.

A third reason is related to the objectives of this study. The objective is not to understand the details of how nonlinear and dynamic-transient loadings affect individual elements within a platform. Very detailed and complex multi-degree of freedom (MDOF) analytical models must be used for such purposes. The objective of this study is to understand how dynamic-transient loadings and the overall nonlinear behavior of the platform interact to influence the effective capacity of the platform to resist intense environmental loading events.[1,2,3]

WAVE FORCE EFFECTS

Wave Records

Results based on three recorded wave amplitude time histories are discussed in this paper. These are wave amplitude time histories recorded in deep water during intense hurricanes in the Gulf of Mexico. They are identified as "Camille", "Juan", and "Elena". These recorded time histories were chosen from the most intense parts of the storms. Recorded wave time histories were chosen for the initial studies because they contain realistic combinations of wave amplitudes, frequencies, and phases. Fig. 2 is an example of one of the recorded wave amplitude time histories used in this study (Elena).

Synthetic wave amplitude time histories also were studied. The component amplitudes, frequencies, and phases in the recorded time histories were determined from Fourier decomposition analyses. The component amplitudes and frequencies were retained and using random phases the amplitude and frequencies were linearly superimposed to develop other realizations of wave amplitude time histories. Two such synthetic time histories were generated from each of the recorded histories.

Short-term time histories having durations of 140 sec were used for the majority of the analyses. This strategy was adopted after analyses of longer term time histories having lengths up to 1,200 sec indicated that the extreme responses (largest ductilities) of the sys-
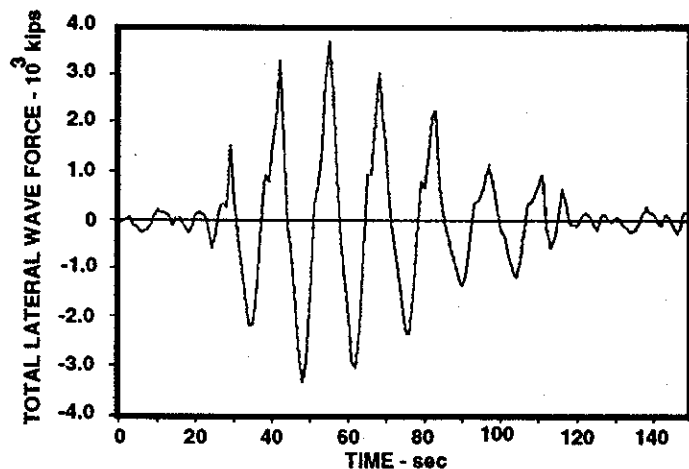
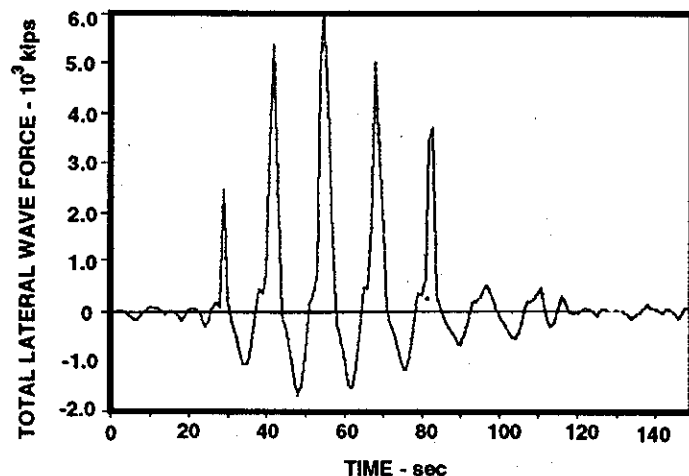Fig. 4. Wave force time history without deck forces (recorded Elena)

Fig. 5. Wave force time history with deck forces (recorded Elena)

Idealized Systems

As a first step, the performance characteristics of elastic-perfectly plastic (EP), non-cyclic degrading (ND), SDOF systems that had periods in the range of $Tn = 1$ to 5 sec were studied. As a base case condition, the viscous damping ratio (D) was assumed to be $D = 5\%$. Damping in the range of 1 % to 10 % was studied. This amount of damping is attributed to structural, foundation, and hydrodynamic sources.[9,10]

Ductility spectra (plots of μ versus Tn) are presented in Fig. 6 as a function of the overload ratio (ratio of peak static force to maximum static load resistance) for EP ND SDOF systems subjected to the recorded Elena force history without deck wave forces (Fig 4).
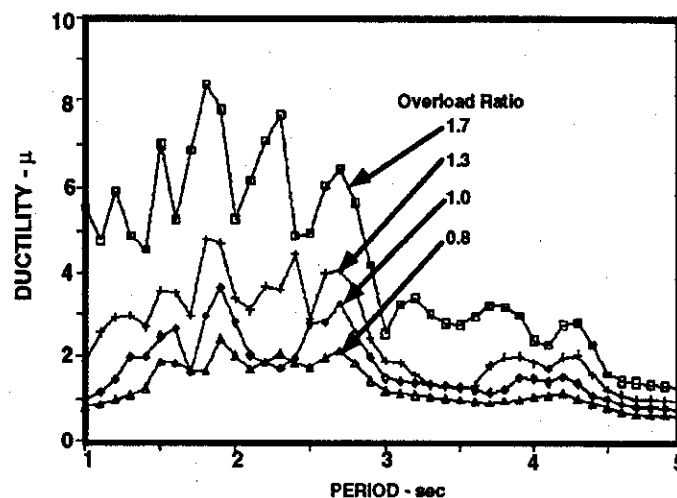

Fig. 6. Elena ductility spectra (recorded without deck wave forces)

There is a general increase in the ductility demand with decreasing period and with increases in the overload ratio. There are significant "peaks and valleys" in the ductility spectra, particularly for $Tn \le 3$ sec. Slight differences in Tn can result in substantial differences in the ductility demands.

The quadratic drag forces due to the wave and current velocities can be expected to produce force harmonics at even and odd multiples of the primary force frequencies.[11-13] The primary force frequencies for the records studied were in the range of 10 to 12 sec. The major peaks in the ductility spectra appear to be associated with these harmonics.

Note that the ductility demand can be greater than one ($\mu > 1$) even though the overload ratio is less than one. This is due to the dynamic forces induced in the system by the loadings.

These ductility demand major peaks and valleys could help explain why adjacent platforms in hurricanes such as "Andrew" could be expected to perform very differently. For the same overload ratio, differences in the mass and stiffness characteristics that could result in differences in the periods of the structures could result in dramatic differences in ductility demands. As will be discussed, differences in damping and cyclic - strain degradation characteristics of the structures could result in additional dramatic differences in ductility demands.

Ductility spectra for the Elena record that incorporated deck wave forces are summarized in Fig. 7. For a given period and the same overload ratio, the ductility demands generally are much larger. This is due to additional dynamic forces imparted to the systems by the wave crest in the deck force spikes. Platforms that have decks that are inundated not only experience a significant increase in the maximum wave forces, but as well there can be an impulsive dynamic loading effect (Fig. 5) that will dramatically increase the ductility demands in the structure.
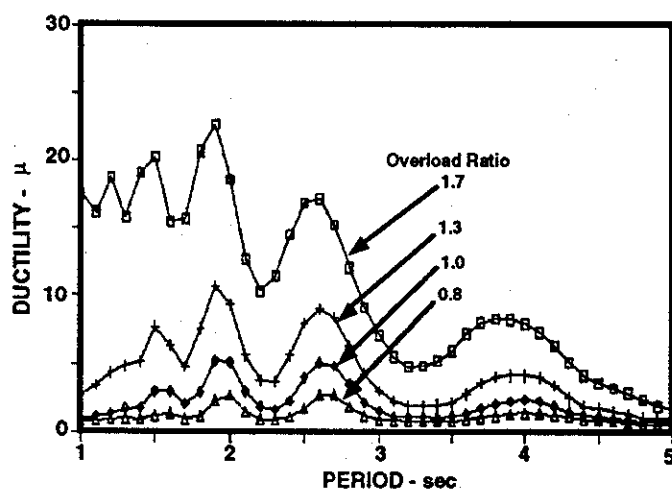

Fig. 7. Elena ductility spectra (recorded with deck wave forces)

The ductility spectra for one of the synthetic time histories based on the recorded Elena amplitude time history (with deck wave

forces) are presented in Fig. 8. Even though the random phase record has the same amplitude and frequency components, it generally produces higher ductility demands than the record that preserved the recorded phases (Fig. 7). The ductility demands depend on the degree of periodicity of the forces that are developed in a particular time history in the sector of the time history that produces the maximum responses. The synthetic time histories generally produced higher ductility demands because of a greater degree of periodicity in the random phase wave amplitude time histories.
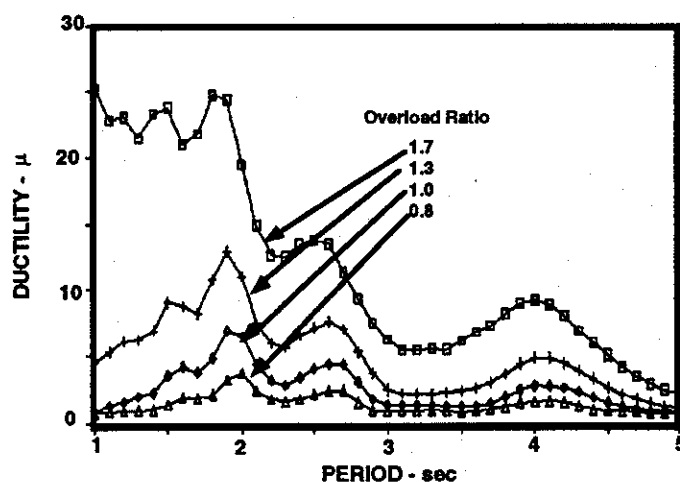

Fig. 8. Elena ductility spectra (random phases with deck wave forces)

Fig. 9 summarizes the ductility spectra for recorded Camille amplitude time history (with deck wave forces). Compared with Fig. 7 there are generally larger ductility demands for given overload ratios associated with the peaks in the spectra and about the same ductility demands for the valleys. Note that the peaks in the ductility spectra at Tn ≈ 4 sec and Tn ≈ 2.6 sec occur at about the same periods in all of the spectra.
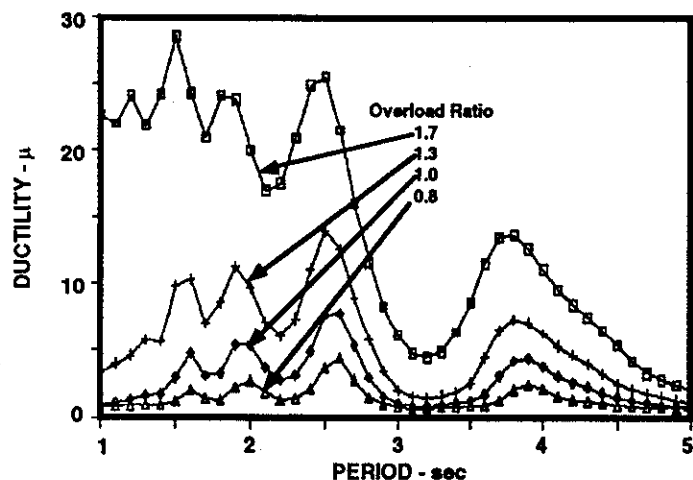
Fig. 9. Camille ductility spectra (recorded with deck forces)

The effects of damping on the ductility spectra are illustrated in Fig. 10. For a given overload ratio, damping in the range of D = 1 % to 10 % generally is not important in determining the ductility demands. The major exception is associated with the primary peaks in the ductility spectra. In the vicinity of these peaks, the lightly damped systems develop significantly greater ductility demands. The high degree of periodicity associated with the primary force harmonics results in a resonance effect that is significantly influenced by damping.
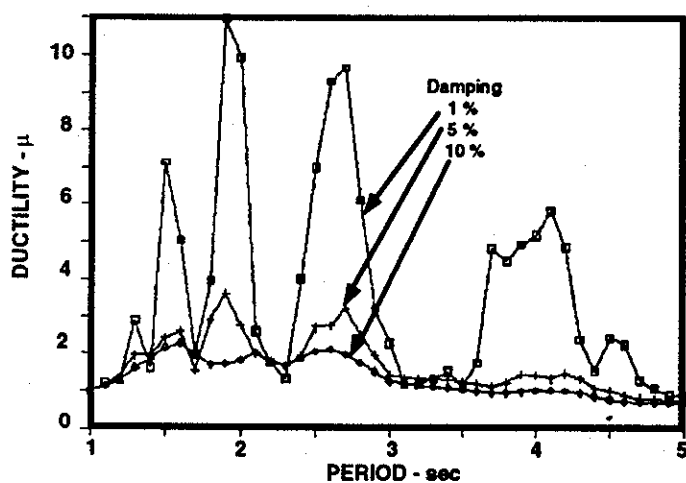

Fig. 10. Elena ductility spectra for various damping ratios (recorded, without deck forces, Fv = 1.0)

SDOF degrading systems also have been studied. The degradation characteristics model those determined from cyclic compression - tension axial loading tests on a tubular braced frame.[14,15] The braces degrade in capacity after the peak buckling strength is reached and also degrade in capacity as a function of the intensity and numbers of cycles (Fig. 11). The brace characteristics that have been studied are based on braces that have effective length to radius of gyration (KL/r) ratios in the range of 50 to 85, diameter to thickness ratios (D/t) in the range of 30 to 40, and are fabricated with A36 steel. These are characteristics typical of braces found in many template-type platforms.
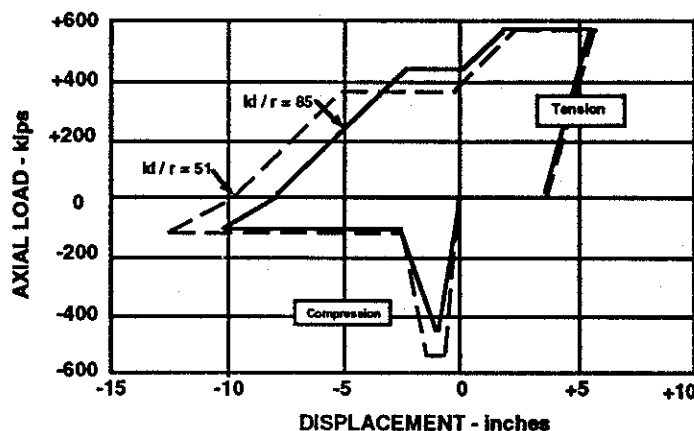

Fig. 11. Analytical model of brace tensile - compressive behavior

The effects of the simulated brace behavior on the recorded Elena (without deck forces) ductility spectra are illustrated in Fig. 12 for an overload ratio of 1.0. The simulated brace does not differ appreciably from that of a comparable EP ND system except in the vicinity of the peaks in the ductility spectra. The lowered energy dissipation capacity in the simulated brace system has an effect on the ductility demand that is similar to that of an EP system with lowered damping. This is an aspect that warrants further study and additional analyses of strain and cyclic degrading SDOF systems are presently being performed.
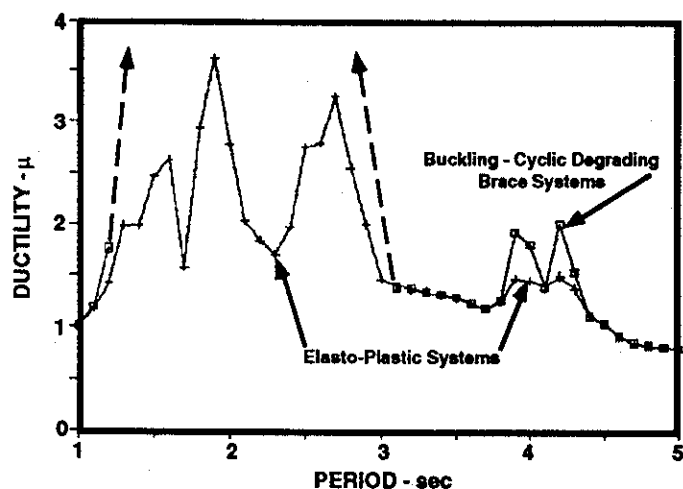
Fig. 12. Degrading brace ductility spectra (Elena, recorded, no deck loading, Fv = 1)

Fig. 13 and Fig. 14 summarizes the results from the analyses of the EP ND systems in terms of the capacity modifier, F_v, and the ductility capacity, μ, for Tn = 1.5 sec, D = 5 %, with and without deck wave loadings for six of the force time histories. The mean F_v–μ trend together with an outline of the upper and lower bounds are shown.
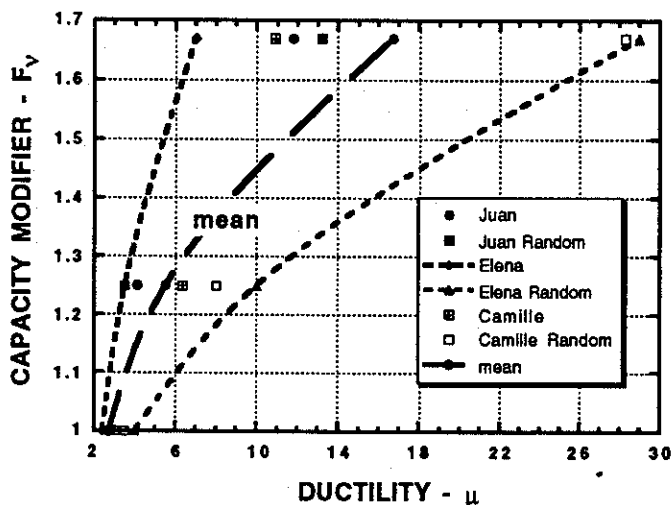

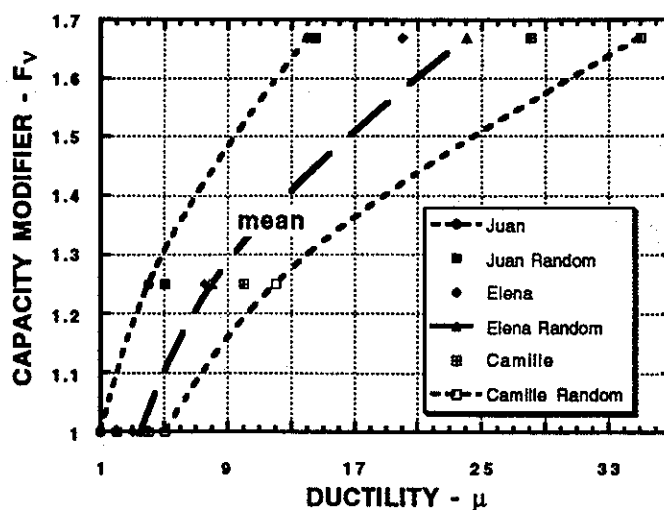**Fig. 13. Capacity factors for given ductility capacities (Tn = 1.5 sec, without deck loadings)**

Fig. 14. Capacity factors for given ductility capacities (Tn = 1.5 sec, with deck loadings)

In the case of no deck wave forces, the Elena recorded and synthetic time histories bracket all of the other results. In the case of the time histories that have deck wave forces, the Juan recorded and Camille synthetic records bracket all of the other results.

For a platform that could develop a ductility capacity in the range of $\mu = 3$ to 4 and for the case of no deck wave forces, the mean capacity modifier would be $F_v \approx 1.2$. This modifier would have a coefficient of variation (V_{Fv}) of $V_{Fv} = 39$ %. For the case with deck forces, $F_v \approx 0.9$.

Platform Response Characteristics

Nonlinear time-history wave force analyses were performed on the platform shown in Fig. 3. The platform was loaded broadside with the recorded Camille and Elena wave amplitude time histories without deck wave forces. The drag coefficients were increased to produce a maximum static lateral storm force overload of $F_v = 1.2$.

The cyclic nonlinear behavior characteristics of the platform braces and pile supporting

soils were based on algorithms that have been developed to describe the behavior of these elements.[14-17] The degradation in strength due to plastic cycling and the increase in strength due to strain rate effects were taken into account. The platform legs, piles, and deck legs were modeled as elastic elements.[6,18] Based on results from ambient vibration measurements that have been performed on this platform[9], damping was assumed as $D = 5\%$. The measurements indicated that the natural period of the platform was $Tn = 1.5$ sec.

Fig. 15 summarizes the results from the recorded Camille nonlinear time history analyses as the time history of the broadside horizontal displacements of the upper platform deck. The first significant yielding of the platform structural system occured at a displacement of approximately $\Delta e \approx 1.0$ ft (the soils yielded at much smaller displacements). The nonlinear behavior was concentrated in the platform's diagonal braces above the bottom bay that contained the skirt pile bracing. The maximum ductility demand was approximately $\mu \approx 3.5$. This result is in good agreement with the ductility results from the SDOF EP ND idealized system results summarized in Fig. 10.
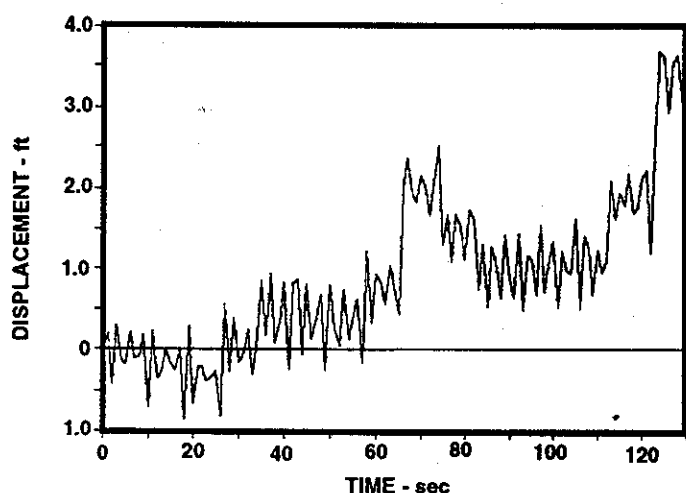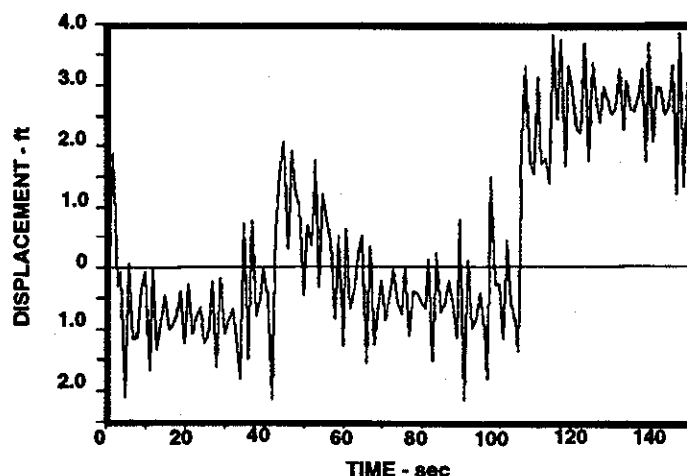

Fig. 16. Platform displacement - time history for overload factor of Fv = 1.2 (recorded Elena)

Fig. 16 summarizes the comparable results from the recorded Elena time history. The peak ductility developed during the force time history was $\mu \approx 4.0$. This result is in good agreement with the ductility results from the SDOF EP ND idealized system results summarized in Fig. 10.

While these comparisons of results from complete platform systems with those from idealized systems are limited, they are encouraging. For the class of platform which has been studied, the analyses indicate that the results from idealized systems can be used to infer the global capacity and ductility behavior of the complete platform system. The load - deformation performance characteristics of the idealized system must be able to mimic the behavior of the complete platform system.

Stewart has performed a study of the ultimate limit state performance characteristics of an 8 - leg platform in a water depth of 459 ft (Tn = 2.0 to 2.3 sec) subject to dynamic wave forcing.[19] Stewart's study results are comparable with those from this study. His results indicate Fv = 1.2. Consideration of semi-ductile member behavior and cyclic loading effects resulted in Fv = 1.07 to 1.0.

Fig. 15. Platform displacement - time history for overload factor of Fv = 1.2 (recorded Camille)

EARTHQUAKE FORCES

The ultimate limit state dynamic response of simplified and complex structural systems subjected to earthquake excitations has been an area of intense research for more than 25 years.[20-27] The concepts of elastic and nonlinear response spectra, ductility based modifications to earthquake induced forces and similar modifications to evaluations of structural capacities are products of these developments.[28,29]

The analyses summarized in this section repeat some of these earlier studies and extend their applications to offshore platforms.

Ground Motion Time Histories

The response of SDOF and MDOF systems subjected to twelve recorded earthquake horizontal acceleration time histories have been evaluated. The recorded time histories were chosen to represent nearby and distant large magnitude earthquakes recorded on sites that could be characterized as firm alluvium. In addition, six synthetic earthquake acceleration time histories were studied. The earthquake acceleration components frequency content, phasing, and energy development characteristics were defined analytically to model the characteristics of large magnitude earthquakes shaking firm alluvium sites.

Idealized Systems

The earthquake loading effects were studied for SDOF, EP ND systems having $T_n = 1$ to 5 sec and $D = 5$ %.

Ductility spectra for two of the recorded earthquake time histories are shown in Fig. 17 (1940 El Centro SE) and Fig. 18 (1971 San Fernando NW). The earthquake acceleration magnitudes were scaled so that the records would contain a peak imposed earthquake force that equaled the yield capacity of the SDOF EP systems ($F_v = 1$), and then each of the records was progressively scaled up to produce increasing overload factors and ductility demands. The F_v factor represents the factor by which the record must be scaled up (accelerations multiplier) to produce a given ductility demand in the SDOF systems.

In many respects, the earthquake ductility spectra are similar to the wave ductility spectra. For SDOF system periods greater than about $T_n = 3$ sec, there is not much variation in the ductilities produced by a given earthquake excitation. For these long period systems large overload ratios are required to produce ductility demands greater than unity. Due to the very small duration of the induced earthquake forces relative to the natural periods of the systems, there is a significant "deamplification" of the induced forces. The peak ductility demands of these long period systems are determined by the peak ground displacements developed during the earthquake time histories.

As for the wave ductility spectra, the ductility demands progressively increase as the periods become smaller. At the small periods, the ductility demands are determined by the peak ground accelerations.

The variability in ductility for a given earthquake record and for the different records decreases as the structure period increases. Even though the records have been scaled to produce equal peak forces on the SDOF EP systems, the systems respond very differently. This is a natural variability that is caused by the differences in the earthquake horizontal acceleration time histories.

Fig. 19 shows the ductility spectra for the same San Fernando time history for SDOF systems that have $D = 10$ %. As for the wave ductility spectra, increased damping decreases the peak magnitudes of the ductility demands and smooth the ductility spectra. However, for this range of periods, the effect of damping is relatively small when compared with the variability introduced by different earthquake time histories.
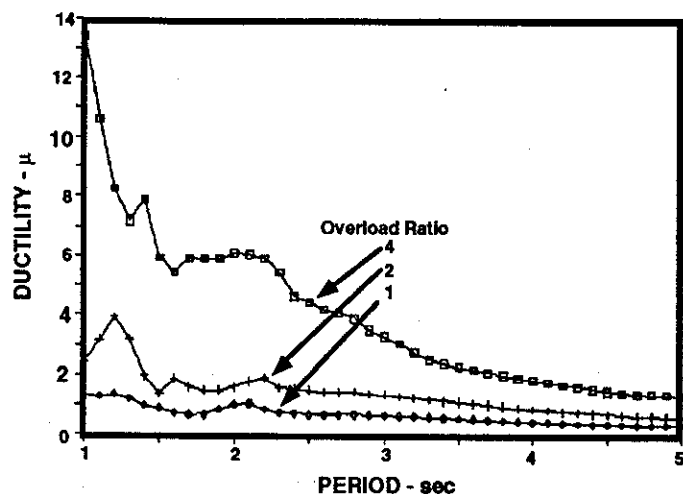
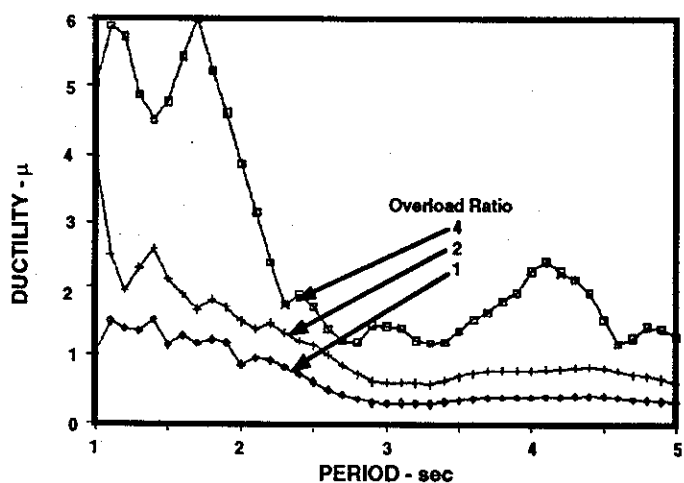**Fig. 17. Ductility response spectra (1979 Imperial Valley, D = 5 %)**

Fig. 18. Ductility response spectra (1971 San Fernando, D = 5 %)

Fig. 20 presents capacity modifiers and ductility capacities for EP ND systems that have Tn = 1 sec and D = 5 % for eight of the recorded earthquake time histories studied. The mean Fv is 50 to 60 % of μ. The coefficient of variation of Fv is in the range of 20 to 40 %. For the synthetic time histories studied, the mean Fv is 60 to 70 % of μ. The coefficient of variation of Fv is in the range of 10 % to 30 %. On

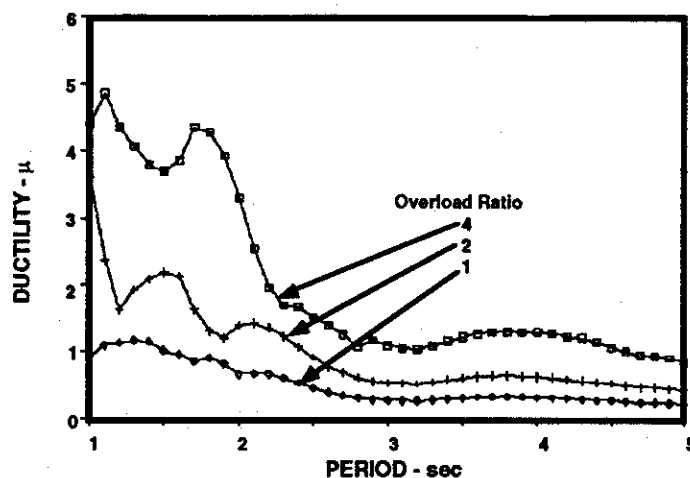the average, for a given Fv, the synthetic records indicated lower ductility demands.

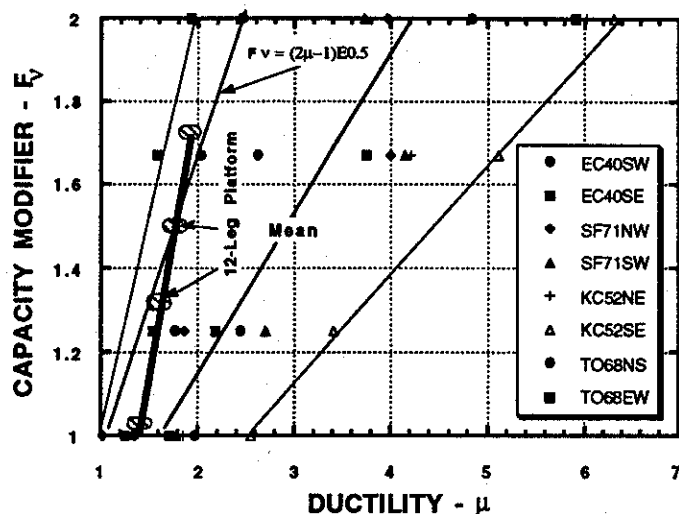**Fig. 19. Ductility response spectra (1971 San Fernando, D = 10 %)**

Fig. 20. Capacity modifiers and ductility demands for recorded earthquakes (Tn = 1.0 sec, D = 5 %)

These results are in good agreement with the results from previous studies of EP ND systems.[20-25] These studies have shown that for this range of Tn and D, that the capacity modifier can be estimated as:

$$Fv = \sqrt{2\mu - 1} \quad \text{.............................(4)}$$

Comparisons of this relationship with the results summarized in Fig. 20 indicate that Eqn. 4 results in a conservative estimate of the mean Fv.

Braced Frame Systems

The response of SDOF and MDOF systems subjected to earthquake excitations have been studied. The response of single and multiple axially loaded brace systems whose nonlinear response characteristics are typical of compressive buckling and tensile yielding tubular braces were analyzed (Fig. 11).

The first set of results were developed for SDOF systems that had nonlinear hysteretic performance characteristics of an axially loaded single brace. The second set of results were developed for MDOF systems that had nonlinear hysteretic performance characteristics of a multi-brace system characteristic of the vertical bracing system of a horizontally K-braced platform (transverse truss of jacket, Fig. 21).

The platform is an unbattered 12-leg drilling and production platform located in a water depth of 58 ft.[6,30] The platform has a natural period of Tn ≈ 1.0 sec (broadside and end-on) and low amplitude damping of D ≈ 5 %. These characteristics have been confirmed with ambient vibration measurements.[6]
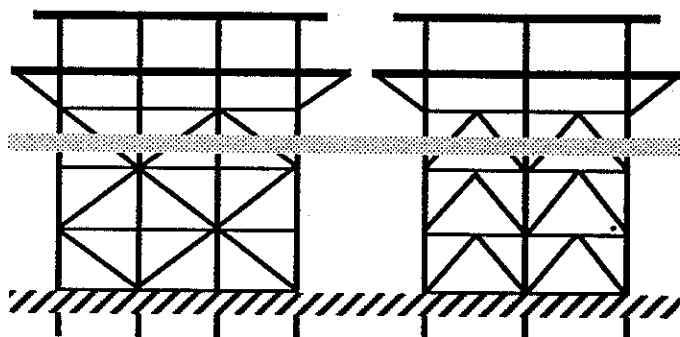
Results also were developed for the complete platform subjected to the three-dimensional El Centro earthquake acceleration time history. The platform braces and pile soils were modeled using nonlinear, hysteretic characterizations appropriate for these elements.[14-17] The deck and leg elements were characterized as being elastic. The intensity of the El Centro record was progressively increased and the global ductility of the platform determined. Results from the analyses of the single and multiple brace systems, from the idealized EP systems, and from the example platform all subjected to the 1940 El Centro time history are summarized in Fig. 22.
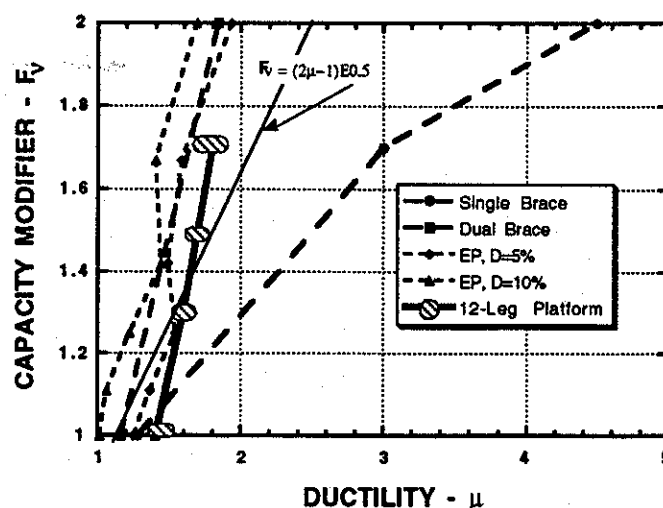

Fig. 22. Performance characteristics of idealized, brace, and platform systems (Tn = 1 sec, D = 5%) subjected to the 1940 El Centro time history

For a given Fv, the EP systems indicate somewhat lower ductility demands than the single brace system and the platform system. The ductility demands for the EP systems having D = 5 % and D = 10 % differ very slightly. The EP systems bracket the behavior of the multiple brace system. The single brace performance indicates much higher ductility demands due to its much lower hysteretic energy dissipation. The interactions of the tensile and compression loaded multiple braces

Fig. 21. Example platform analyzed to determine earthquake response characteristics

result in a system that has high hysteretic energy dissipation. The platform system indicates ductility demands that are reasonably well characterized by the EP system that has D = 5 %.

Fig. 23 summarizes the results from this study for SDOF EP ND systems having a period of Tn = 2 sec. and damping D = 5 % for the recorded earthquake time histories. The mean results and upper and lower bounds from the time history analyses are indicated.
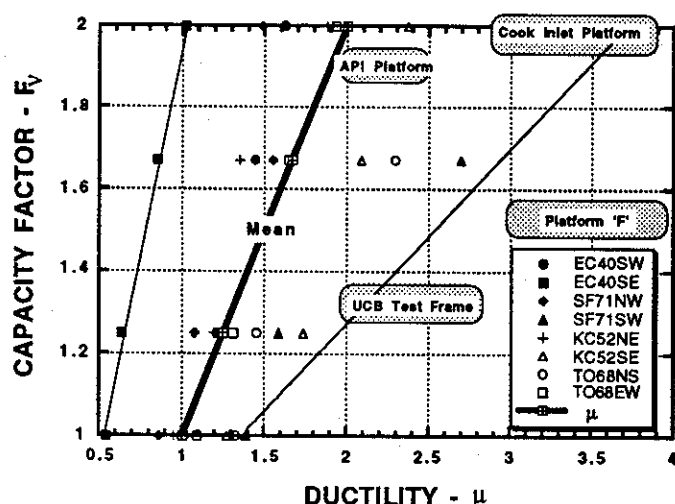

Fig. 23. Capacity factors and ductility demands for synthetic earthquakes (Tn = 2.0 sec, D = 5 %)

For this range of SDOF system periods and damping, previous studies have indicated that the mean capacity modifier can be evaluated as:[20-25]

$$F_V = \mu \quad\quad\quad\quad\quad\quad\quad\quad\quad\quad (5)$$

This estimate provides and excellent fit to the mean results from this study.

The performance characteristics of strain and cyclic degrading SDOF systems also have been studied.[35] For systems having periods Tn ≥ 2 sec. the mean results can be evaluated as:

$$F_V = \mu \, \alpha \quad\quad\quad\quad\quad\quad\quad\quad\quad (6)$$

where α is the residual strength ratio (Table 1, Fig. 1).

Presented in Fig. 23 are results from nonlinear time history analyses of complete platform systems having natural periods of Tn = 2 sec to 3 sec.[6,31-33] The API platform [31] and Platform 'F' [6] are conventional 8-leg and 12-leg platforms, respectively. The Cook Inlet platform is a steel X-braced tower-type platform.[32,33]

Results from a scale model of a vertical frame that was extensively tested to determine its performance characteristics when subjected to earthquake induced force time histories also are shown (indicated as "UCB test frame").[14,15] This test frame also has been studied extensively by Bazzurro and Cornell.[34] The results developed by Bazzurro and Cornell are very similar to those summarized here.

For a given Fv, the complete platform systems generally indicate greater ductility demands than indicated by the SDOF EP ND systems. The platform performance characteristics are described much better by the SDOF strain - cyclic degrading system results for residual strength ratios of α = 0.75 to α = 0.50.

CONCLUSIONS

Capacity modifiers for platforms subjected to extreme condition wave and earthquake forces have been developed to adjust the ultimate limit state lateral load resistance determined from static push-over analyses. These capacity modifiers are functions of the transient loadings and the performance characteristics of the platform systems (Table 1).

Based on the verification analyses that have been performed on complete platform systems and for the class of structures and perfor-

mance characteristics studied, results from idealized systems can be used to develop reasonable evaluations of global capacity modifiers if appropriate nonlinear hysteretic characteristics are chosen for the idealized systems. Additional analyses of platform structures subjected to ultimate limit state intensity loadings and analyses of idealized nonlinear hysteretic systems are needed to further develop these results.

ACKNOWLEDGMENTS

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